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KEY ISSUES IN THE ANALYSIS OF PILES IN LIQUEFYING SOILS

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ABSTRACT

Two methods for analysis of piles in liquefying soils are discussed in this paper: an advanced method for dynamic analysis based on the effective stress principle and a simplified analysis based on the pseudo-static approach. The former method aims at an accurate simulation of the complex liquefaction process and soil-pile interaction while the latter is a design-oriented approach that uses conventional engineering parameters and modelling for estimation of the maximum pile response. This paper discusses some key issues in the implementation of these analysis methods with reference to the assumptions used in modelling the soil-pile interaction in liquefying soils.

Keywords: Effective stress analysis, lateral spreading, liquefaction, pile, pseudo-static analysis

INTRODUCTION

Behaviour of piles in liquefying soils is very complex involving rapid change in stiffness and strength of soils, large ground deformation and significant inertial loads from the superstructure. A rigorous analysis simulating this process in detail, such as the seismic effective stress analysis, imposes high demands on the user in terms of required input data and understanding of the adopted numerical procedures. On the other hand, when using design-oriented analyses based on the pseudo-static approach, one encounters great difficulties in the selection of appropriate values for the parameters of the simplified analysis because nearly all parameters used in the simplified model are subject to large variation in the course of the pore pressure build-up and eventual liquefaction. Thus, the key issues in the analysis of piles are quite different for the advanced seismic effective stress analysis and simplified pseudo-static analysis. This paper addresses some of the key issues in the application of these two methods of analysis to piles in liquefying soils.

SOIL PILE INTERACTION IN LIQUEFYING SOILS

Soil-pile interaction in liquefying soils is a very intense dynamic process that involves significant changes in the soil characteristics and loads on pile over a short period of time during and immediately after the strong ground shaking. Some typical features of the ground response and loads on piles in liquefying soils are illustrated in Figure 1. During the intense ground shaking in loose saturated sandy deposits, the excess pore water pressure rapidly builds up until eventually it reaches the level of the effective overburden stress σ_v' and the soil liquefies. In the example shown in Figure 1a from the 1995 Kobe earthquake, the excess pore pressure reached the maximum level after only 6-7 seconds of intense shaking, and this was practically the time over which the soil stiffness reduced from its initial value to nearly zero. The intense reduction in stiffness and strength of the soil was accompanied with equally rapid increase in the ground deformation, as illustrated with the solid line in Figure 1b where horizontal ground displacements within the liquefied layer are shown. Note the cyclic nature and relatively large amplitude of these displacements. The peak displacement of about 40 cm occurred just

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before or at the time of development of complete liquefaction in the layer and was accompanied with high ground accelerations of about 0.4g. During this phase of intense ground shaking and development of liquefaction, the piles were subjected to kinematic loads due to ground movement and inertial loads due to vibrations of the superstructure. Both these loads are oscillatory in nature with magnitudes and spatial distribution dependent on a number of factors including ground motion characteristics, soil density, presence of non-liquefied crust layer at the ground surface, and predominant periods of the ground and superstructure, among others.

In sloping ground or backfills behind waterfront structures the liquefaction may result in unilateral ground displacements due to lateral spreading, as indicated with the dashed line in Figure 1b. Lateral

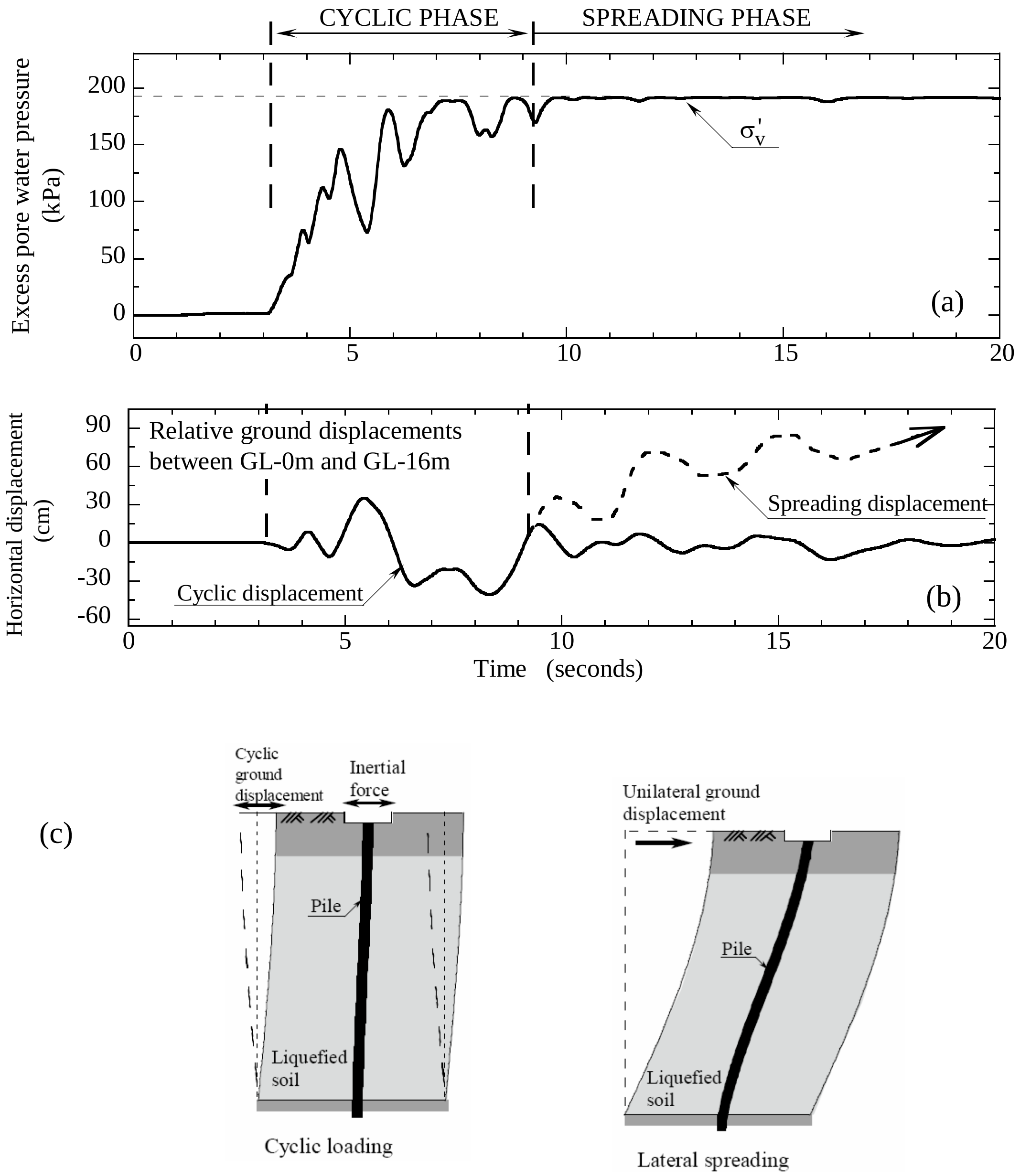

Figure 1. Illustration of ground response in liquefying soils and effects on piles: (a) Excess pore water pressure; (b) Lateral ground displacement; (c) loads on pile during the cyclic phase and lateral spreading

spreads typically result in large permanent displacements of up to several meters in the down-slope direction or towards waterways. Provided that driving shear stresses exist in the ground, lateral spreading may be initiated during the intense pore pressure build up, at the onset of liquefaction or after the development of complete liquefaction. As compared to the cyclic phase of the response, ground displacements are approximately one order of magnitude bigger and inertial loads are relatively smaller during the lateral spreading, as illustrated schematically in Figure 1c. These large differences in liquefaction characteristics and loads on the pile between the cyclic phase and lateral spreading phase need to be accounted for in the analysis of piles.

SEISMIC EFFECTIVE STRESS ANALYSIS

The effective stress analysis permits evaluation of seismic soil-pile interaction while considering the effects of excess pore water pressure and highly nonlinear stress-strain behaviour of soils in a rigorous dynamic analysis. This method basically aims at very detailed modelling of the complex liquefaction process through the use of advanced numerical procedures. In principle, the effective stress analysis permits simulation of the entire process of pore pressure development, onset of liquefaction and post-liquefaction behaviour including associated ground deformation and loads on piles during both cyclic phase and lateral spreading phase of the response. For these reasons, the seismic analysis based on the effective stress principle has been established as one of the primary tools for analysis of liquefaction problems. Over the past three decades, the application of this analysis gradually has expanded from 1-D analyses of a level ground to more complex 2-D analyses involving earth structures and soil-structure interaction problems. Recently, attempts have been made to apply this method to a three-dimensional analysis of large-deformation problems, as described below.

A comprehensive study on pile foundations in liquefiable soils has been recently carried out in Japan, with a principal objective to investigate the behaviour of piles in liquefying soils undergoing lateral spreading, from both experimental and numerical viewpoints. Within this project, a series of shake-table experiments on piles in liquefying soils undergoing lateral spreading was conducted at the Public Works Research Institute (PWRI), Tsukuba, Japan (Tanimoto et al., 2003). For all experiments, Class-B predictions were made using two different constitutive models and numerical procedures for 3-D effective stress analysis. The principal objective of the numerical simulations was to assess the accuracy and capability of advanced 3-D effective stress analyses in predicting liquefaction-induced lateral flow and pile group behaviour. Note that both methods of analysis have been extensively verified and have shown very good performance in simulations of well-documented case histories, seismic centrifuge tests and large-scale shake table tests of liquefaction problems (e.g., Cubrinovski et al., 1999; 2001; Uzuoka et al. 2002; 2007).

Various factors were varied in the aforementioned shake table experiments such as the amplitude and direction of shaking (transverse, longitudinal and vertical), mass of the superstructure and number and arrangement of piles. A typical physical model used in these tests is shown in Figure 2 consisting of a 3x3 pile foundation embedded in a liquefiable sand deposit, located in the vicinity of a sheet pile wall. By and large, the numerical predictions were in good agreement with the observations in the experiment capturing the rapid pore pressure build-up, development of liquefaction and subsequent ground flow around the foundation. In fact, the response of the foundation piles were very well predicted by both methods for all experiments, as indicated in Figure 3a where computed and measured horizontal displacements at the pile head are shown for different tests. As indicated in Figure 3b, however, the analyses underestimated the displacement of the sheet pile wall. It was found that the prediction of the large lateral movement of the sheet pile wall including instability in the backfills and foundation soils was the most difficult to accurately predict with the advanced seismic analyses.

A number of issues are important when conducting a seismic effective stress analysis as above, but probably the most critical one is the performance of the constitutive soil model, both in terms of its modelling capability and proper implementation by the user. It is essential that the constitutive model

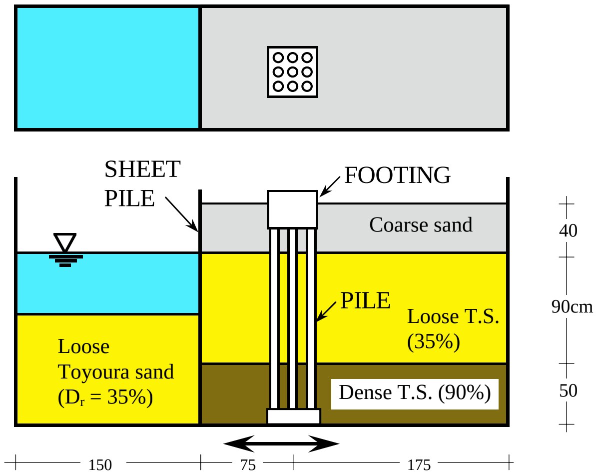

Figure 2. Schematic plot of physical model used in the shake table test

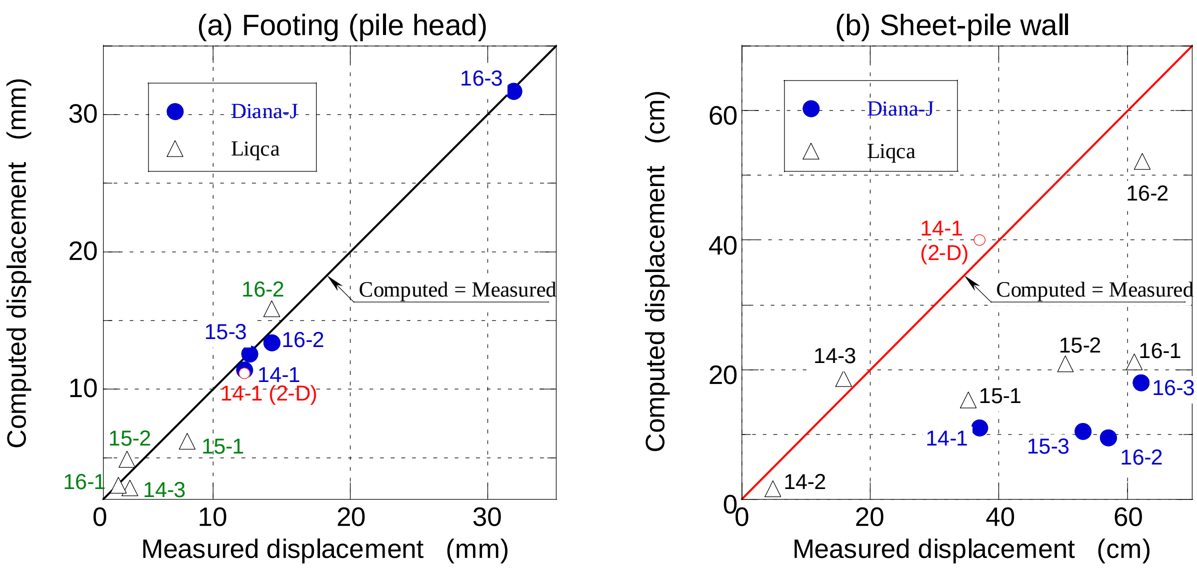

Figure 3. Comparison between computed and measured displacements of footing and sheet pile

provides reasonably good accuracy in predicting the excess pore pressures and ground deformation in order to allow proper evaluation of the soil-pile interaction effects.

The initial stress conditions and anticipated ground deformation pattern are equally important for a correct prediction of pile behaviour. In the above study, for example, detailed initial stress analyses were conducted in order to identify the initial stress in the soil deposit before the application of shaking. Specific boundary conditions and soil-pile interfaces were also defined in order to allow development of large displacements and deformation pattern associated with lateral spreading. In fact, the latter was found to be one of the major reasons for the underestimation of sheet pile displacements in the analyses. The aforementioned modelling issues together with inherent limitations of a particular numerical procedure define the second critical issue in the application of the seismic effective stress analysis. The complexities associated with current constitutive soil models and numerical procedures probably explain why this analysis in spite of the unparalleled capability has not found yet an adequate use in the engineering practice.

PSEUDO-STATIC ANALYSIS

Unlike the advanced effective stress analysis which aims at simulating the complex soil-pile interaction as liquefaction develops through time, the pseudo-static analysis aims at estimating the maximum pile response by using a relatively simple model and small number of engineering parameters. The key issue in such analysis is thus the selection of appropriate values for the parameters that represent the soil conditions and loads at the time when the maximum response of the pile develops. As discussed in the previous sections, the liquefaction characteristics and lateral loads on piles vary significantly in the course of the development of liquefaction and are quite different between the cyclic phase and subsequent lateral spreading phase of the response. For this reason, the cyclic phase and lateral spreading phase have to be treated separately in the pseudo-static analysis.

A conventional beam-spring model allowing for stiffness and strength reduction in the liquefied layer, large movement of the liquefied soil, lateral soil pressure from the crust layer and lateral load on the pile due to inertial effects is shown in Figure 4. While this model generally permits modelling of multiple layers with different load-deformation spring properties, in essence it distinguishes between three distinct layers: non-liquefiable crust layer at the ground surface, liquefiable layer and non-liquefiable base layer. As indicated in Figure 4, degraded stiffness and strength are used for the liquefied soil, and it is assumed that the crust layer moves as a rigid body on top of the liquefied soil.

The characterization of nonlinear behaviour of the soil and pile shown in Figure 5 is probably the simplest one that allows adequate treatment of nonlinear behaviour of the soil and pile. Here, the bilinear p-δ relationships for the soil are defined by an initial stiffness using the conventional subgrade reaction approach and by an ultimate lateral soil pressure, p_{max}. The subgrade reaction coefficients k can be evaluated using empirical correlations based on the elastic moduli of the soil or SPT blow count while the ultimate lateral pressure for the non-liquefied layers can be estimated using a factored Rankine passive pressure, as described in Cubrinovski and Ishihara (2004).

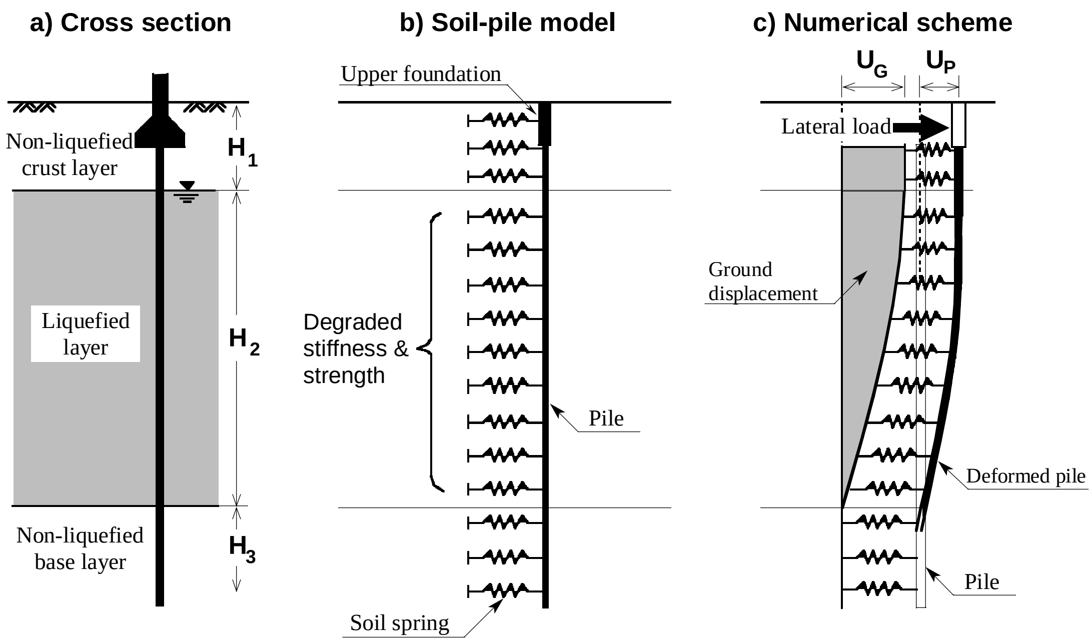

Figure 4. Typical FEM beam-spring model for pseudo-static analysis of piles

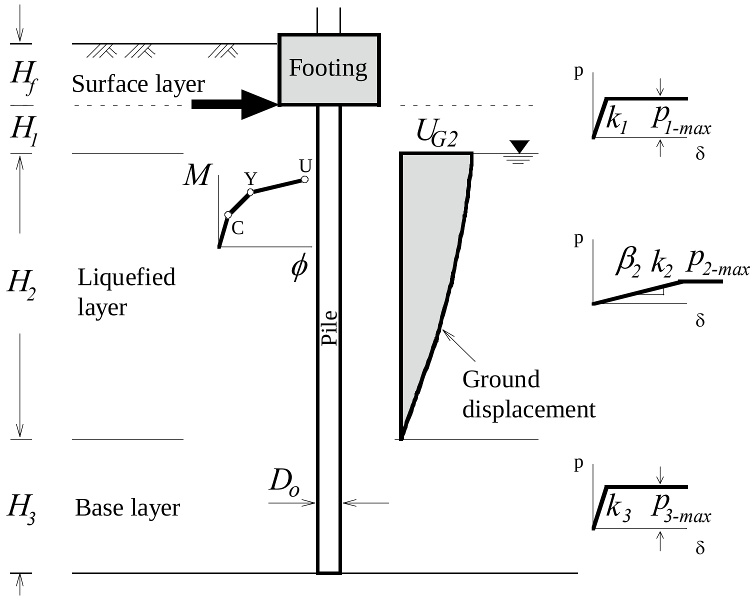

Figure 5. Characterization of nonlinear behaviour and input parameters of the model

Key parameters in this model are the magnitude of lateral ground displacement (U_{G2}), ultimate lateral pressure from the crust layer (p_{1-max}), and stiffness and strength reduction in the liquefied layer as represented by the stiffness degradation factor β_2 and ultimate pressure p_{2-max} respectively. Some guidance in the selection of the ultimate pressure from the crust layer and variation in the magnitude of lateral ground displacement can be found in Cubrinovski at al. (2007). Here, effects of the ultimate pressure form the liquefied soil are examined somewhat in detail.

Cyclic Phase

Assuming that the peak response of the pile during the cyclic phase occurs at or before the onset of liquefaction, which is a reasonable assumption according to observations from experiments and analyses, then the following reasoning can be applied to the analysis of piles: (i) The value of β_2 commonly varies within a relatively small range of values between 1/20 and 1/10; (ii) The magnitude of cyclic ground displacements can be estimated reasonably well using simple procedures analogue to those for evaluation of liquefaction triggering based on empirical SPT / CPT charts, as suggested by Tokimatsu and Asaka (1998) for example; (iii) The relative displacement between the soil and the pile is often less than that required for mobilizing the ultimate soil pressure from the crust and liquefied layers; (iv) In addition to the large kinematic loads due to lateral ground movement, the piles are subjected to significant inertial loads from the superstructure. The above basically implies that often the particular values of β_2, U_{G2} and p_{2-max} are not critically important, but rather the key issue in the analysis of piles during the cyclic phase is how to combine the kinematic loads and inertial loads on the pile since the peak values of these oscillatory loads do not necessarily occur at the same time. Clear and simple rules for combining the ground displacements and inertial loads from the superstructure in the simplified pseudo-static analysis have not been established yet, though some suggestions may be found in Tamura and Tokimatsu (2005) and Liyanapathirana and Poulos (2005).

Lateral Spreading Phase

In the lateral spreading phase, the potential variation in key parameters is much more significant and involves: (i) Variation in β_2 over relatively wide range of values between 1/1000 and 1/50; (ii) Large uncertainty in the magnitude of lateral displacement and scatter in the estimates based on empirical correlations for lateral spreads; (iii) Relative displacements between the soil and pile sufficiently large to mobilize the ultimate soil pressure from the crust layer and liquefied layer; (iv) Small contribution of inertial loads relative to the kinematic loads. Thus, in the case of lateral spreading, the values of p_{1-max}, β_2, U_{G2} and p_{2-max} involve great variation and uncertainty associated with the strength and stiffness of liquefying soils, post-liquefaction spreading displacements and ultimate pressure from the non-liquefied crust layer at the ground surface. Detailed discussion on the modelling of the crust layer and selection of p_{1-max} is given in a companion paper presented at this conference whereas here the combined effects of parameters of the liquefied layer U_{G2}, β_2 and p_{2-max} are briefly illustrated through an application of the analysis to a case study.

STIFFNESS AND STRENGTH OF THE LIQUEFIED SOIL

The pile foundation of twin bridges crossing the Avon River in Christchurch, New Zealand, was analysed using series of seismic effective stress and pseudo-static analyses. Various combinations of loads and liquefaction characteristics including pile-group and soil-structure interaction effects were considered in these analyses. The pseudo-static analyses presented in this paper are used only to demonstrate the effects of the ultimate pressure from the liquefied layer on the pile response.

Figure 6 shows the soil profile and SPT blow count at the site including the adopted three-layer interpretation of the deposit. The soils between 2.5 m and 17.5 m were considered liquefiable, with a dense silty sand base layer below 17.5 m depth. The water table was estimated at 2.5 m depth thus defining a non-liquefiable crust layer at the ground surface. The 1.2 m diameter reinforced concrete piles are rigidly connected to a pile cap and extend from 2.5 m to 23 m depth below ground level.

The interaction in the liquefied layer can be treated in a simplified manner by an equivalent linear p-δ relationship, i.e. with no limiting soil pressure. Alternatively and more rigorously, a limit can be placed on the pressure exerted by the liquefied soil. One approach in doing this is to use the residual strength of the liquefiable soil S_u as defined by Seed and Harder (1991) using empirical correlation with the SPT blow count, as shown in Figure 7. Since the scatter of the data is quite significant for this correlation, it was adopted to use three different S_u values in the pseudo-static analysis corresponding to an upper bound (S_{u-ub}), best-fit (S_{u-bf}) and a lower bound value (S_{u-lb}) respectively. The purpose of this parametric study was to examine the effects of the ultimate lateral pressure from the liquefied soil on the pile response.

Figure 8 comparatively shows the computed bending moments and pile displacements for the analyses with different S_u values. Note that an analysis using an equivalent linear p-δ approximation was also

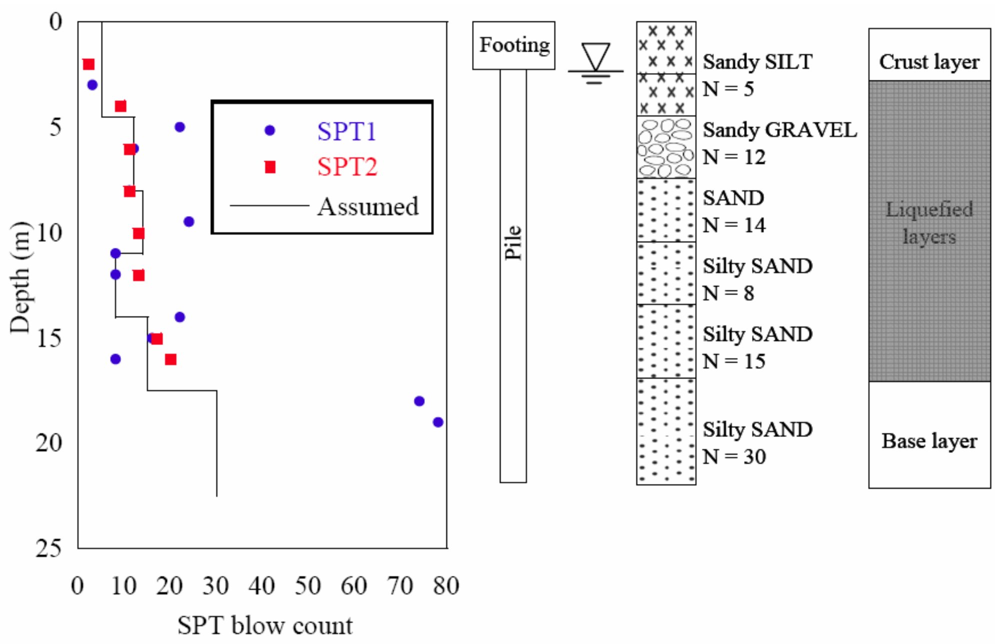

Figure 6. Soil profile and SPT blow count at the investigated site

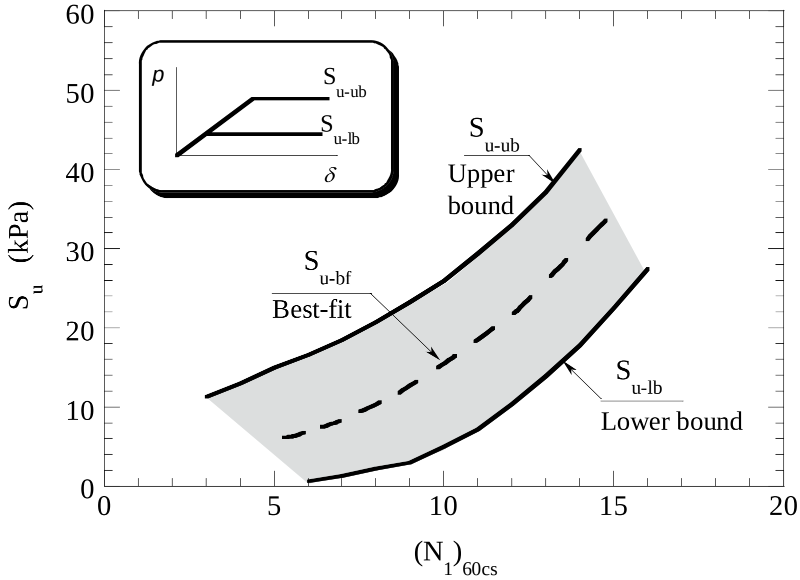

Figure 7. Residual strength (S_u) of sandy soils back-calculated from case histories (after Seed and Harder, 1990)

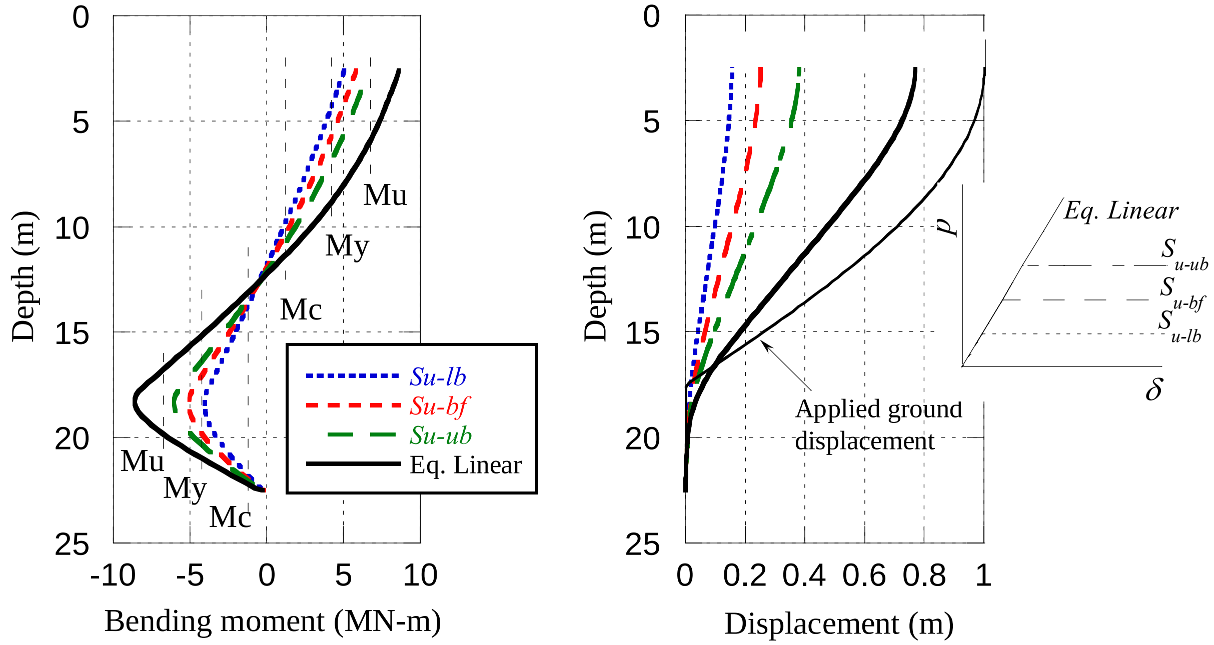

Figure 8. Effects of ultimate pressure from the liquefied soil on the pile response

conducted for comparison purpose. By and large, the pile response decreases with decreasing ultimate pressure from the liquefied layer.

Figure 9 shows the relative displacement between the soil and the pile plotted together with the reference yield displacement of the soil, for the three analysis cases with different S_u values. Here, the shaded areas denote zones over which yielding occurs in the soil. In other words, throughout these depths, the ultimate soil pressure is applied to the pile. Note that the resultant load on the pile increases with increasing ultimate lateral pressure from the soil, with the largest response being observed when $S_{u\text{-}ub}$ was used as a limiting lateral soil pressure. The equivalent linear analysis overestimates the pile response and is not applicable in this case. The relative contributions of the crust and liquefied layers to the total pile also change with the value of S_u. As the value of S_u decreases the role of the liquefied layer diminishes.

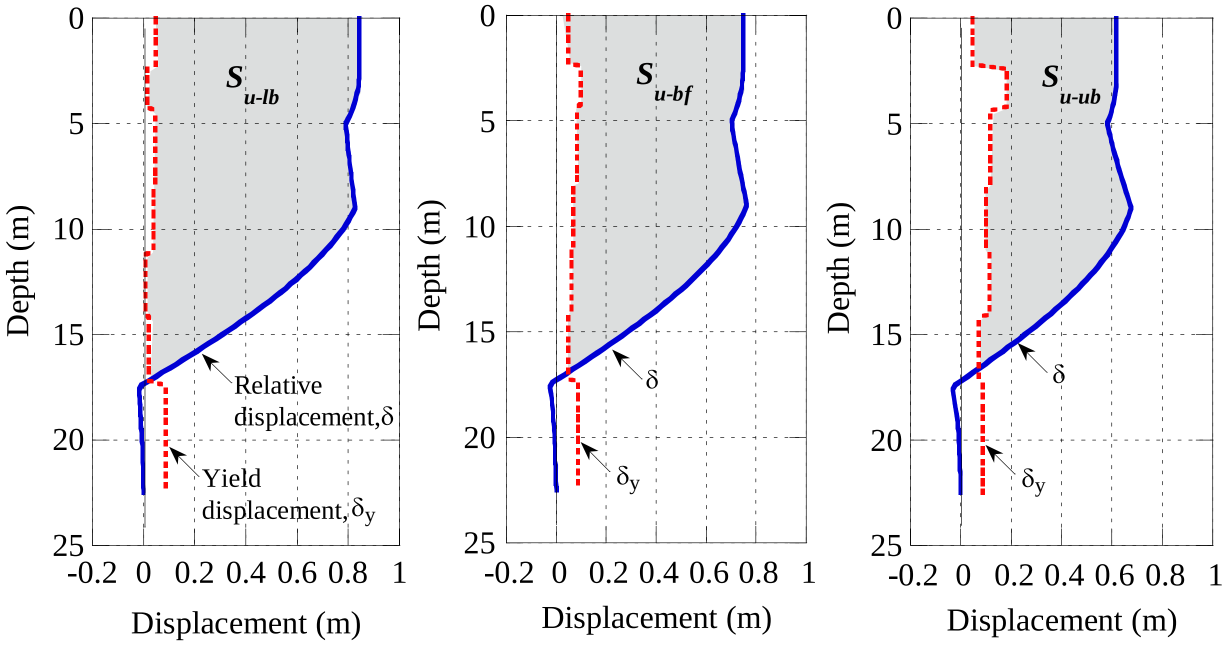

Figure 9. Effects of ultimate pressure from the liquefied soil on soil yielding

The reasoning behind placing limits upon the ultimate pressure exerted from the liquefied soil is to avoid unrealistic loads being imposed in situations with very large ground displacements. Figure 10 shows how the bending moment of the considered pile varies with different levels of ground displacement, for an assumed value of β_2 = 1/50. It can be seen that when limits are placed on the ultimate pressure, different levels of ground displacement yield virtually the same response. This clearly demonstrates that for any given set of values for β_2 and $p_{2\text{-}max}$ there exists a threshold magnitude of lateral ground displacement above which the pile response is practically unaffected by the magnitude of ground displacement. Hence, for many analysis cases, a specific determination of the magnitude of lateral spreading displacement may not be needed.

CONCLUDING REMARKS

The effective stress analysis aims at detailed modelling of the complex soil-pile interaction in liquefying soils, and hence, this analysis procedure is quite complex and burdened by the large number of parameters and expertise needed for its execution. Two critical issues in the seismic effective stress analysis are: (i) the performance of the constitutive soil model, both in terms of its modelling capability and proper implementation by the user, and (ii) details of numerical modelling including initial stress state, boundary conditions and possible effects of the adopted numerical procedures.

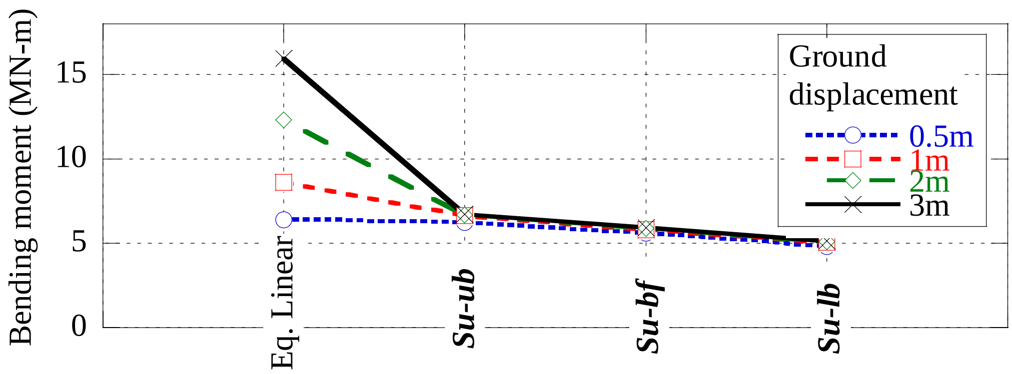

Figure 10. Effects of ultimate pressure from the liquefied soil on soil yielding

The pseudo-static analysis is a simple design-oriented approach that uses conventional engineering parameters and modelling for estimation of the maximum pile response. Liquefaction characteristics and lateral loads on piles are quite different between the cyclic phase and subsequent lateral spreading phase of the response, and therefore, these two phases have to be treated separately in the pseudo-static analysis.

When evaluating the pile response during the cyclic phase, the key issue in the pseudo-static analysis is how to combine the kinematic loads due to ground movement and inertial loads from the superstructure. For the lateral spreading phase on the other hand, the combined effects of parameters of the crust layer and liquefied layer p_{1-max}, U_{G2}, β_2 and p_{2-max} are important. It is important to note, however, that for an assumed stiffness and strength of the liquefied soil (set of values for β_2 and p_{2-max}), there is a threshold lateral ground displacement U_{G2} above which the pile response is practically unaffected by the magnitude of ground displacement. This simplifies the use of the pseudo-static analysis and eliminates the need for an accurate estimate of the magnitude of lateral spreading displacement.

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